Wind Direction Estimates from Synthetic Aperture Radar Imagery of the Sea Surface

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LONG-TERM GOALS

1. We will investigate the range of near-surface mean wind directions with respect to the orientation of common marine atmospheric boundary layer (MABL) quasi-two dimensional phenomena seen in synthetic aperture radar (SAR) imagery. In doing so, we will provide empirically-derived guidelines on how to distinguish the SAR-signature of one feature from another.

2. We will provide the impact of position errors in numerical weather model-analyzed synoptic scale storms and fronts on the wind direction-dependent retrieval of wind speed from SAR. This will be accomplished via a thorough error analysis of CMOD-4 with an emphasis on wind direction errors at varying incidence angles, and varying wind-relative look directions.

OBJECTIVES

1. We will investigate the range of near-surface mean wind directions with respect to the orientation of common MABL quasi-two dimensional phenomena seen in SAR imagery of the sea surface. We will provide empirically-derived guidelines on how to distinguish the SAR-signature of one feature from another (see Figure 1 for examples of quasi-two dimensional phenomena seen in SAR imagery of the sea surface). We have outlined the scope of this portion of the research in Sikora and Young (2002). The quasi-two dimensional MABL phenomena that we will study are elongated cellular convection, buoyancy-driven / shear-organized roll vortices, inflection point-induced roll vortices, shear-driven gravity waves, and topographically-driven gravity waves.

2. We will provide the impact of position errors in numerical weather model-analyzed synoptic scale storms and fronts on the wind direction-dependent retrieval of wind speed from SAR via a thorough error analysis of CMOD-4 with an emphasis on wind direction errors at varying incidence angles, and varying wind-relative look directions (see Figure 2 for an example of such an error). We will use the results of this error analysis to develop automated or semi-automated detection and correction algorithms for displaced cyclones and frontal wind shift lines. These algorithms will improve the accuracy of SAR wind speed retrieval in conjunction with model-analyzed wind direction fields.

APPROACH

The basis of the feature-identification research will be SAR imagery provided to us by collaborators at

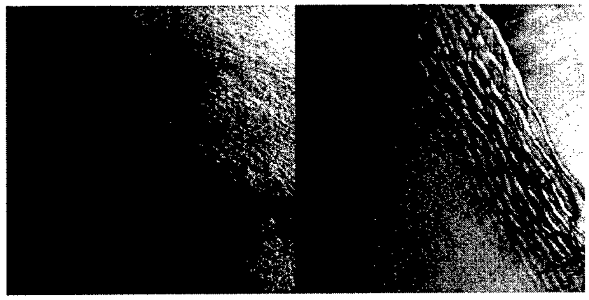

***Figure 1.** Radarsat-1 SAR image (left) depicting the signature of roll vortices. The 300 m pixel image is approximately 270 km by 270 km. The image was acquired at C-band, horizontal polarization, off the north east coast of the United States at 2242 UTC on 6 March 1997. The top of the image is directed towards 348°T. (Provided courtesy of JHUAPL, © CSA) ERS-1 SAR image (right) depicting the signature atmospheric gravity waves associated highly ageostrophic flow near a front. The 180 m pixel image is approximately 90 km by 90 km. The image was acquired at C-band, vertical polarization, over the Caspian Sea at 0723 UTC on 12 May 1996. The top of the image is directed towards 012°T. (Provided courtesy of Werner Alpers and ESA, © ESA)*

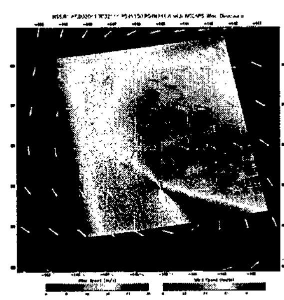

***Figure 2.** SAR wind speed image for 10 February 2002 generated by the Johns Hopkins University Applied Physics Laboratory. The image on was generated using NOGAPS wind directions. The image contain an example of an erroneous hour-glass signature (at approximately 55^o N, -145^o) resulting from the mis-positioning of the cyclone center by NOGAPS. Arrows denote the corresponding model wind speed and direction.*

Johns Hopkins University Applied Physics Laboratory (JHUAPL). This SAR imagery will be cross-referenced with corresponding in situ, remote sensing, and modeling data. This supporting data will be used to assess both the type of phenomena depicted in a given SAR scene and the relationship between its orientation and the near-surface mean wind direction. Given that hundreds of SAR images of both the Northwest Atlantic Ocean and the Northeast Pacific Ocean are available to us, our study will provide a robust assessment of both feature orientation with respect to near-surface mean wind direction and of how to discern one feature from another. Using this knowledge, we will endeavor to develop image processing algorithms mimicking our ability to distinguish between quasi-two dimensional phenomena based on their structure in the SAR backscatter field. With these algorithms, it will be possible to automate the determination of the relative angle between near-surface wind direction and the alignment quasi-two dimensional features in the SAR imagery.

Correction of model wind direction fields for misplaced synoptic features follows three steps: First, detection and location of the SAR error signature. Second, reposition the cyclone center or frontal

wind shift line to eliminate this error. Third, morph the surrounding model wind direction field so that the far field is unaffected by the position correction.

For the cyclone misplacement problem, the first step involves locating the model-analyzed vortex and then quantifying the degree to which the SAR derived wind speed field around the cyclone center matches the position-error signature. If the signature pattern explains at least 80% (a tunable parameter) of the variance, the vortex is classed as misplaced and the maximum range for which this condition is met is used as a measure of the error-signature size. Because the weak and strong sectors of the error signature are oriented primarily with respect to the track direction its alignment provides little direct guidance as to the direction of cyclone position error. Instead, features of the raw backscatter field such vortex-center-calms and -spirals are analyzed to suggest likely vortex positions. Selection between candidate positions and tuning of the final selection will be automated via minimization of the error signature criterion given above. The center is then displaced to its true location while points at greater radii from the center are displaced less, i.e. a single control point morphing. The diameter of the region affected should be proportional to the displacement distance with the constant of proportionality being a second tunable parameter.

Frontal position correction will follow the same three steps selection between multiple candidates will not be required for computing displacement of a linear feature. Depending on our success in developing an automatic detection algorithm for the more subtle frontal position error signatures, human analysis of frontal position and displacement may be required.

WORK COMPLETED

1. We have documented the SAR-signatures of synoptic-scale cold fronts, warm fronts, occluded fronts, and secluded fronts, including their mesoscale and microscale sub-structures. The basis for these findings is the analysis of some 6000 RADARSAT-1 SAR images from the Gulf of Alaska and from off the east coast of North America. This analysis yielded 158 cases of well defined frontal signatures: 22 warm fronts, 37 cold fronts, 3 stationary fronts, 32 occluded fronts, and 64 secluded fronts.

Most synoptic-scale atmospheric fronts share two generic SAR-observable features. The first is a near zero order change in the mean backscatter while the second is a near zero-order change in the character of the micro-α to meso-γ-scale eddy SAR signatures.

Cold front-specific SAR signatures include meso-γ-scale lobe and cleft instability, meso-γ-scale vortices, meso-γ-scale Kelvin-Helmholtz instability, and convective signatures to the immediate rear of the cold front. Warm and occluded front-specific SAR signatures include pre-frontal jets, meso-β-scale vortices, and meso-γ or micro-α-scale banding aligned nearly perpendicular to the front associated with gravity waves.

For more details on the above findings, refer to the following publications:

Young, G. S., T. D. Sikora, and N. S. Winstead, 2005: Use of synthetic aperture radar in fine-scale surface analysis of synoptic-scale fronts at sea. *Weather and Forecasting*, in press.

Sikora, T. D., G. S. Young, and N. S. Winstead, 2004: Use of synthetic aperture radar in the fine-scale analysis of synoptic-scale fronts at sea. *Preprints, Thirteenth Conference on*

Interactions of the Sea and Atmosphere, AMS, Portland, ME, 9-13 August 2004, CD publication.

These studies will primarily aid our second objective (morphing). Moreover, we ascertained that the wind direction information revealed by the SAR-signatures of mesoscale and microscale eddies is of great importance in locating and typing synoptic scale fronts. Thus, there is a direct two-way connection between these studies and our first objective.

2. We have completed a climatology of the error signatures as a function of frontal orientation, wind direction, and position error direction in fronts and cyclones. These results were explained using quantitative modeling with CMOD-4. Matlab code was developed to recognize these signatures and to execute single-control-point morphing of cyclone positions and multi-control-point morphing of frontal positions.

RESULTS

1. We have documented the SAR-signatures of synoptic-scale cold fronts, warm fronts, occluded fronts, and secluded fronts, including their wind direction-related mesoscale and microscale sub-structures. The basis for these findings is the analysis of some 6000 RADARSAT-1 SAR images from the Gulf of Alaska and from off the east coast of North America. This analysis yielded 158 cases of well defined frontal signatures: 22 warm fronts, 37 cold fronts, 3 stationary fronts, 32 occluded fronts, and 64 secluded fronts. An example of our frontal identification findings can be seen in Figure 3.

2. We have developed manual morphing rules for hourglass, weak-band, and strong-band SAR signatures, including cause and cure, to aid us in our second objective. The cause of the hourglass signature is the misplacement of a wind direction singularity. The cure is to morph the point at the center of the hourglass signature to the true position of the singularity. The cause of the weak and strong-band signatures is an improperly placed wind direction shift across a front. The cure is to morph the wind direction field so as to achieve a discontinuity in wind direction along the front and more nearly uniform wind directions on each side of the front. We have used our morphing software to demonstrate that substantial improvements in the SAR-derived wind speed field can be obtained by correctly morphing the numerical-model-analysis-derived wind direction fields before application of the CMOD-4 wind speed diagnosis algorithm.

IMPACT/APPLICATIONS

The research described herein fulfills ONR objectives by working towards the integration of standard meteorological theory and synthetic aperture radar data with the goal of providing high-resolution remotely sensed estimates of near-surface wind field and meteorology in *in situ* data-sparse regions over the ocean, including the coastal zone. For example, the frontal identification work we've completed thus far will help train forecasters to use SAR to its full potential in marine synoptic scale frontal analysis. The morphing software we've developed will allow users to obtain accurate SAR-derived wind speeds even when numerical model analyses used for the wind direction field have position errors for key synoptic features.

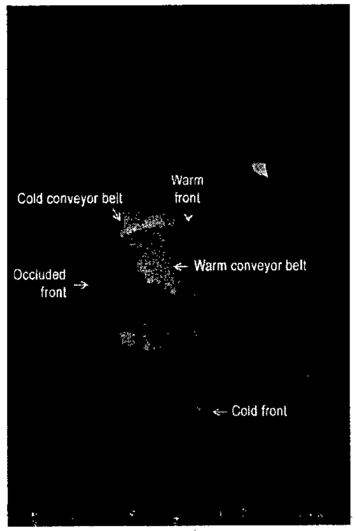

Figure 3. Radarsat-1 SAR image depicting the the intersection of a cold front, warm front, and occluded front. The 600 m pixel image is approximately 800 km by 450 km. The image was acquired at C-band, horizontal polarization, over the Bering Sea at 0500 UTC on 31 October 1999. The top of the SAR image is directed towards 348°T. (Provided courtesy of JHUAPL, © CSA)

RELATED PROJECTS

Project Co-PI George Young has an NSF-funded SAR project that supports the development of analysis tools essential to our ONR-funded research. The Matlab CMOD-4 code was developed jointly with NSF-co-PI Nathaniel Winstead. An interactive SAR wind field analysis program with a graphical user interface was developed by George Young as part of this project and will serve as the host application for the automated and interactive wind-direction field morphing routines developed under ONR funding.

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Sikora, T. D., and G. S. Young, 2002: Wind-direction dependence of quasi-2D SAR signatures. *Proceedings, International Geoscience and Remote Sensing Symposium 2002*, IEEE, Toronto, CA, 24-28 June 2002, 1887-1889.

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Sikora, T. D., G. S. Young, and N. S. Winstead, 2004: Use of synthetic aperture radar in the fine-scale analysis of synoptic-scale fronts at sea. *Preprints, Thirteenth Conference on Interactions of the Sea and Atmosphere,* AMS, Portland, ME, 9-13 August 2004, CD publication.

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